Dynamic Forces Exerted by Moving Vehicles On a Road Surface

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This paper describes an apparatus for measuring the forces exerted at a point on a road surface by the wheels of moving vehicles. Detailed results are presented of measurements of three force components: vertical force, and longitudinal and transverse horizontal force components. The investigation included a study of the influence on these forces of tire inflation pressure, speed, acceleration, wheel load, height of measuring stud above road surface, etc.

Seven different vehicles were used covering a range of wheel (tire) load from 135 kg to 2,540 kg (300 lb to 5,600 lb), and a speed range of 15 kph to 75 kph (6 mph to 47 mph).

● MANY PAPERS have been written concerning the interaction between wheel and road, right from the early days of the self-propelled vehicle. In 1913 a study (1) was made of the suspension system of motor vehicles leading to an early theory of the dynamic behavior of cars and trucks. In this and subsequent work an attempt was made to find the magnitude of the impact forces applied by the wheel and how they are influenced by tire and spring stiffness, by shock absorbers, damping factors, shape and height of obstacles, and speed, etc.

Much of the experimental work done after World War I, until the early thirties, was concerned with comparisons between solid and pneumatic tires to help in questions of legislation on vehicle wheels and tires. Various methods for determining the vertical impact forces and their relation to the static wheel load have been developed. They can be divided into the following groups: (1) recording the deflection of the tire or of the sidewalls of the tire, (2) recording the deflection of the main springs and the acceleration of the unsprung masses, (3) recording the acceleration of sprung and unsprung masses, (4) measuring the deflection of the road surface, (5) measuring the variation of inflation pressure, and (6) direct measurement of the forces on the road surface.

It is not proposed to discuss these methods here, but it may be noted that most of the experimental work was carried out in order to determine the relation between static and dynamic wheel loads and the relative importance of the various influencing factors. A method for comparing the forces exerted by various tires at different speeds was published in 1934 (2), where a pipe filled with water was installed in the road and the increase in water pressure under a passing wheel was measured electrically.

A more recent publication (3) described a system developed for weighing vehicles in motion using electronic recording. The influence of the self-oscillations of vehicles on the forces applied to the road has also been studied (4). Before the solid tire had disappeared from the roads, some tests were carried out to measure the distribution of the three components of the force per unit area under static conditions (5, 6). It was found that the average vertical force per unit area (calculated from wheel load and area of contact) was up to 30 percent smaller than the actual measured maximum. If a tire rolls over a hemisphere of 11.3-mm diameter the force per unit area under static conditions underneath this obstacle increases up to 30 kg per sq cm for pneumatic tires, and is roughly independent of wheel load and position in the contact area. It was assumed that under dynamic conditions, that is, short-time loading, these forces per unit area would be increased by about 50 percent.

Just before World War II Markwick and Starks (7) made some measurements of the vertical and horizontal forces exerted on a small area (a fraction of a square inch) in a road surface by stationary and moving wheels. Some of their findings are of interest to compare with the results described in this paper. Pneumatic tires were found to exert maximum vertical stresses approximately 1½ times the inflation pressure, inde-

TABLE 1

RANGE OF VARIABLES

Vehicle	Speed Range, kph (mph)	Acceleration Range, percent g	Deceleration Range, percent g	Range of Inflation Pressure, kg per sq cm	Stud Height, mm
Lloyd 600 Kombi	15-56 (9-35)	10-20	20-30	1.75	0, 2.5, 5.5
Land-Rover	10-30 (6-19)	20-30	30-40	1.75-2.1	0, 5.5
Chevrolet Sedan	10-75 (6-47)	10-30	20-40	2 1	0, 2.5, 5.5
Chevrolet Brookwood (loaded)	10-50 (6-31)	15-25		1.75-3.4	0, 2.5; 5.5
Chevrolet 3-ton Truck (loaded)	15-55 (9-34)	10-15	20-30	F 2.45-4.2 R 4.2 -4.9	0, 2.5, 5.5
Ford V8 Truck (loaded)	15-48 (9-30)			F 3.15 R 4.9	0, 2.5, 4.0; 5.5
Chevrolet 6-ton Truck (loaded)	15-30 (9-19)	10-20		R 4.9-7.0	0, 2.5

pendently of speed. Horizontal stresses under a stationary wheel were found to be directed inwards, and were up to 50 psi, whereas under a solid tire these stresses were directed outwards. Under a moving tire and with dry conditions, the horizontal stresses showed rapid alternations as the tire left the road whereas under wet conditions these alternations did not occur.

The present paper describes a systematic study of the three components of the force exerted by the tire of a moving vehicle on a circular flat stud one square inch in area lying in the road surface. The investigation has included a study of the influence of all the more important factors, listed in Table 1. In all, seven different vehicles were used enabling a range of single wheel load from 135 kg (for a light car) to 2,540 kg (for a loaded truck) to be covered. The latter figure would correspond (using the normal dual wheel arrangement of a truck) to an axle load of 10,160 kg (approximately 22,000 lb). Table 2 gives some relevant particulars of the vehicles.

DESCRIPTION OF APPARATUS AND TEST SITE

The apparatus for measuring road surface stresses consists essentially of a stress recorder box, which is installed under the road surface, and electronic and photographic gear housed in a mobile laboratory on the roadside (Fig. 1).

The stress recorder box is installed in a special manhole on the center line of the road. A manhole cover, surfaced with similar material to that of the road, is fitted over the recorder box leaving the road surface continuous except for the circular force-measuring stud, which is 1 sq in. in area and can be made either flush with the surface or projecting above it by adjustable amounts (Fig. 2). On either side of the stud on the center line of the road two dip switches project with which the vehicle speed is measured and the oscilloscope triggered. The operation of these switches is described in more detail in Appendix A.

TABLE 2

DATA ON VEHICLES

Vehicle	Total Weight, kg	Wheel Load		Tire				Wheel Base, m
		Front, kg	Rear, kg	Wheel	Size, in.	Ply Rating	Width of Tread, cm	
Lloyd 600 Kombi	750	205 (driven)	135	Front Rear	5.00-15	-	9.8 8.3	2.35
Land-Rover	1,460	370	380	Front Rear	6.00-16	-	11.1 11.4	2.24
Chevrolet Sedan	1,650	420	405	Front Rear	6.70-15	6	11.6 9.9	2.93
Chevrolet Brookwood (loaded)	2,300	480	650	Front Rear	8.00-14	4	12.7 12.1	2.98
Chevrolet 3-ton Truck (loaded)	5,080	680	1780/2	Front Rear	7.00-20 7.50-20	10 10	12.4 12.6	4.15
Ford V8 Truck (loaded)	5,230	700	2,330	Front Rear	7.00-20 9.75-18	8 12	12.1 18.9	3.96
Chevrolet 6-ton Truck (loaded)	6,600	680	2,540	Front Rear	8.25-20 9.00-20	10 10	17.5	3.98

Figure 1. General view of the test site.

The force-measuring stud is supported by two independent spring systems, as shown in Figure 3, which are deflected proportionally to the vertical and horizontal components of the force applied to the stud.

Normally the longitudinal horizontal force is measured. In order to measure the transverse horizontal force, the stress recorder box is turned through 90 deg and measurements are then made in the normal way.

Condenser plates fitted to the spring systems in conjunction with the electronic gear described in Appendix A are used to convert the mechanical deflections of the spring systems into electrical signals which can be photographed on an oscilloscope screen.

The spring systems together with the associated force transfer beams and stud have been so designed that a maximum horizontal force of 75 kg and a maximum vertical force of 190 kg can be measured. It was further ensured that the resonant

Figure 2. Close-up showing stress-recorder in position.

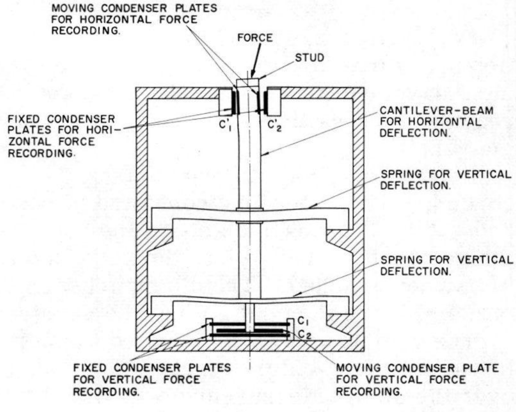


Figure 3. Diagrammatic sketch of stress-recorder.

frequencies of both spring systems were considerably higher than the frequency corresponding to the shortest loading time likely to be investigated. For a vehicle speed of 80 kph (50 mph) the induced frequency corresponds to about 60 cps, whereas the natural resonance of both spring systems was about 500 cps. However, it was found that the recorded traces were modulated by the natural spring vibrations at vehicle speeds in excess of 60 kph (37 mph).

The experimental setup is shown in Figure 4. An oscillator supplies an input signal of about 8 volts R.M.S. at 150 kilocycles per sec to the stress recorder. Electrical signals from the stress recorder are filtered and adjusted in a sub-chassis before being fed to a double-beam oscilloscope where the traces are photographed. A regulated power supply serves both the stress recorder and sub-chassis. The triggering signals from the dip switches are fed to the oscilloscope via a two-way switch and multi-vibrator. The signals for starting and stopping the electronic timer are obtained from a parallel switch attached to one dip switch and reach the timer via the sub-chassis which contains the battery supplying the current. The recorder cables are taken via an underground pipe from the manhole to the mobile laboratory at the side of the road.

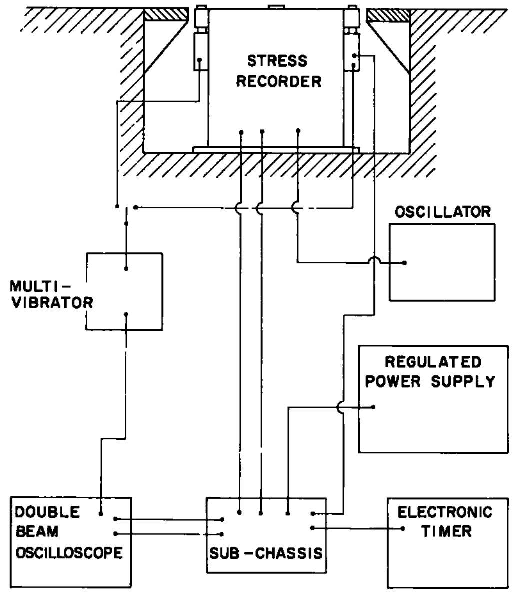


Figure 4. Block diagram of apparatus.

The experiments were carried out on a lightly trafficked provincial road near Pretoria. The road had a fairly even profile, both transverse and longitudinal, and was fairly horizontal and straight at the test site. A continuous white line was painted for about 60 m (200 ft) in both directions along the center line of the road to assist in driving the vehicles accurately over the stud.

To facilitate the determination of the exact point on the tire at which the stud was contacted, dust was lightly applied to the road prior to each run at a point one circumference of the tire away from the stud in the direction from which the vehicle was to approach. This enabled a print of the tire to be obtained on a strip of paper next to the stud which showed the transverse position of the tread relative to the stud.

EXPERIMENTAL PROCEDURE

For each of the vehicles used, the wheel load, wheel base, tire size and tire inflation pressure were recorded, the tire pressure being checked at regular intervals during a day's work. The acceleration and deceleration of the vehicle was found by taking readings on a calibrated braking efficiency meter clamped to the steering column of the vehicle.

Before each test was carried out the apparatus was adjusted and set ready for recording. The procedure consisted of balancing out the DC potentials for the horizontal and vertical forces and setting the oscilloscope sensitivity and beam-sweep speed to the required values so that the recorded trace would fall within the area of the screen to be photographed. The dip switches, as well as the control switches on the sub-chassis, were then set so that the required wheel would trigger the oscilloscope.

The vehicle was then signalled to approach and the camera exposure knobs pressed just before the vehicle reached the stud, and released again after the wheel had passed over the stud. Measurements of both horizontal and vertical forces were made from the photographic traces. Actual vehicle speeds were calculated from the timer readings and the length of the wheel base.

Figure 5. View of lever arrangement used for horizontal force calibration.

Calibration of the apparatus was carried out at regular intervals during a day's testing. For vertical-force calibration weights were stacked on the stud in increments up to 180 kg and, with the oscilloscope on continuous sweep, readings taken of the voltages corresponding to the weights on the stud. A similar calibration was used for the horizontal calibration using a lever arrangement by which known horizontal loads could be applied in increments up to 60 kg on the stud in either direction (Fig. 5). Typical calibration curves are given in Figure 6. Measurements of the "deviation," that is, the relative position of the tire center line to the stud, were made for each test run, as described above. All the testing was done under dry conditions.

DISCUSSION OF RESULTS OBTAINED

General

The following factors, which influence the forces applied at a point on the road surface, were varied:

1. Wheel load.
2. Tire size.
3. Inflation pressure.
4. Vehicle speed.
5. Measuring stud height above road surface.
6. Acceleration and deceleration.
7. Front and rear wheel.

8. Transverse position of contact, that is, distance between the center of the stud and the center line of the contact area of the tire tread, referred to in this paper as the "deviation."

9. Type of tread (normal road or cross-country type).

Other factors which may also influence the forces applied, but which were not studied, are:

1. Shape of contact area of the measuring stud.
2. Size of contact area of the stud.
3. Variation of the coefficient of friction between tire and stud, that is, roughness of the stud surface, material of the stud, wetness of the tire and/or the stud surface, etc.

The stud was made of aluminum and had a flat surface, serrated to a depth of 0.3 mm.

Of the three components of the total force exerted on the stud, only two could be measured at a time; for example, the vertical component and one of the horizontal components. Most of the tests done consisted of measuring the vertical component and the longitudinal horizontal component, that is, the horizontal component in the direction of motion of the vehicle. The order of magnitude of the transverse component, that is, horizontal at right angles to the direction of motion of the vehicle, was, however, also established in a small series of tests.

Before discussing the test results in detail, some comments on the scatter in the results should be made. It is well known that the load on a wheel is not constant under dynamic conditions, that is, as soon as the vehicle starts moving (4, 8, 9), the load varies in magnitude and in frequency, and is influenced by irregularities in the road surface, inflation pressure, speed, running conditions such as acceleration or cornering, the suspension system of the vehicle and its general dynamic behavior. Scatter was also caused by other experimental factors. The driver had to concentrate on running the right wheel over the stud in the required position and could not always watch the speedometer carefully, thus leading to small differences of speed in a given test series. It can be assumed, therefore, that the vehicle was not always in the same phase of self-oscillation during the contact-time, that is, the load on the wheel varied. Furthermore, there is the influence of tread pattern and of small out-of-balance effects of wheel and tire, which could lead to variation in the forces applied to the stud. The so-called "deviation," that is, the position of the stud relative to the center line of the tread, was measured as exactly as possible but, here again, small errors were unavoidable. Another potential source of variation in the longitudinal horizontal components under rear wheel tests was the unavoidable variation in applied torque at constant speed.

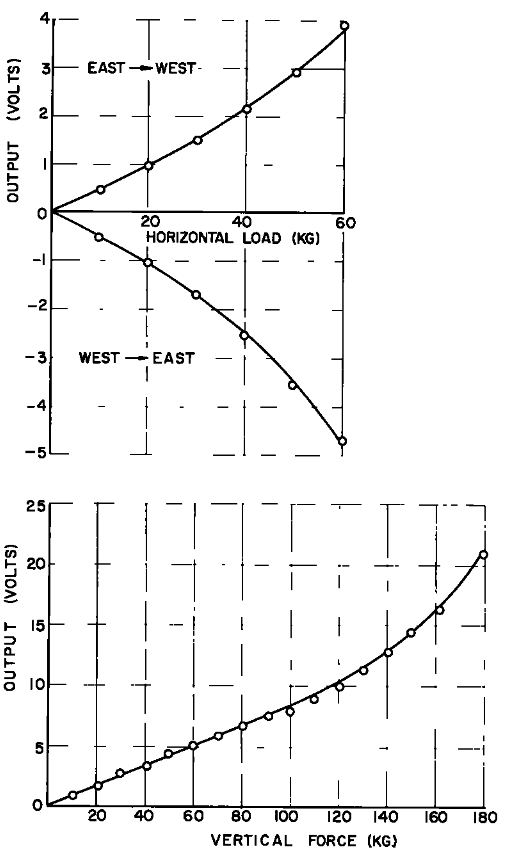


Figure 6. Voltage-force calibration curves.

Shape of the Force Recordings

Before discussing the results obtained and the influence of the different variables, some general comments can be made on the shape of the force-time traces recorded on the oscilloscope.

Vertical Force Component. Typical force recordings are shown in Figure 7. In each record the lower trace represents the vertical force component. It will be noted that the side slopes of the force-time traces are almost linear, and that the top part is either horizontal or of a saddle-like form, usually having two peaks of similar height. When the deviation is great, so that only a part of the surface area of the stud is in contact with the tire, the shape of the vertical force recording approaches that of a half sine-wave.

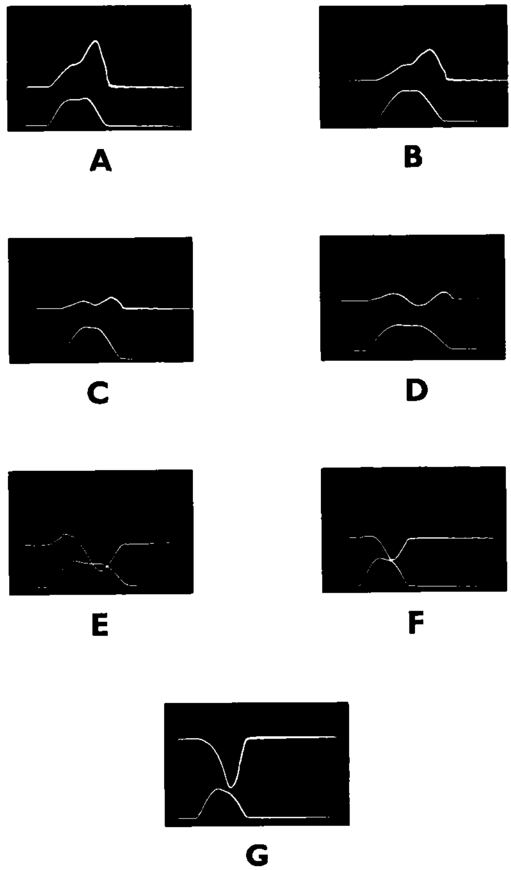


Figure 7. Typical force recordings showing longitudinal and vertical traces. Chevrolet Sedan: rear wheel; tire, 6.70-15; wheel load, 405 kg; stud height, 5.5 mm; inflation pressure, 2.1 kg per sq cm; deviation, -3 to +0.5 cm.

A. Speed: 25 kph (15.5 mph), acceleration: 0.37 g.
B. Speed: 22 kph (13.5 mph), acceleration: 0.23 g.
C. Speed: 25 kph (15.5 mph), acceleration: 0.10 g.
D. Speed: 19 kph (12 mph), acceleration: none.
E. Speed: 43.5 kph (27 mph), acceleration: none.
F. Speed: 34 kph (21 mph), deceleration: 0.13 g.
G. Speed: 34 kph (21 mph), deceleration: 0.39 g.

Tread pattern, stud height above surface and acceleration or deceleration all influence the shape of the vertical force recording, but the basic shape for the tread's center line does not vary much. For vehicle speeds in excess of 60 kph (37 mph) the vertical and horizontal force diagram is modulated by a vibration with a frequency of 500 cps, which is attributed to the natural frequency of the mechanical part of the recorder system. The amplitude of this vibration is, however, very small in comparison with the signal.

Longitudinal Force Component. The shape and magnitude of the longitudinal horizontal force component depends very much on the condition of vehicle motion. Figure 7 gives a typical example of a driven wheel for acceleration, constant speed and deceleration. The upper trace in every diagram of Figure 7 represents the longitudinal force component, a trace above the zero line representing force on the stud against the direction of vehicle travel, and below the line with the direction of travel. If a large torque is applied to a wheel, as in accelerating or decelerating a vehicle, the longitudinal force trace has one predominant peak in the latter half of the time of contact, as shown in Figure 7a and b for accelerating, and 7f and g for decelerating. The traces show clearly the variation of the direction of the longitudinal peak force with degree of acceleration and deceleration. Running the car with constant speed over the stud (Fig. 7d and e), the longitudinal force trace of the driving wheel has in most cases three peaks, but sometimes only two. The first and the third one are always opposite to the direction of motion, the second one mostly in the direction of motion. At constant speed the difference between the shapes of the recordings for rear and front wheel are small, except in the case of the loaded trucks, where the driving wheel develops a comparatively high first peak which results in a greater area under that part of the force-time curve, representing the force driving the vehicle forwards.

Transverse Force Component. Figure 8 gives, as an example, two typical recordings of the transverse component. The shape of the force-time diagram is similar to a half sine-wave if the stud area is not in contact with the center line of the tire tread. These forces acting on the stud are always directed towards the center line of the tread, and are very small at small deviations.

A B

Figure 8. Typical force recordings showing transverse and vertical traces. Chevrolet Brookwood (loaded): rear wheel; tire, 8.00-14; wheel load, 650 kg; stud height, zero; inflation pressure, 2.8 kg per sq cm.

A. Speed: 17 kph (10.5 mph), acceleration: none, deviation: 3 cm.
B. Speed: 15 kph (9.5 mph), acceleration: none, deviation: 5.5 cm.

Resultant Forces

A vectorial picture of the resultant horizontal forces is given in Figure 9 for the rear wheel of the loaded Chevrolet Brookwood using a stud height of zero. It can be taken as a typical example for constant speed conditions, showing the instantaneous distribution of the horizontal resultant during the length of contact and over the contact area. Static tests carried out by Martin (6) gave a similar picture with force vectors pointing roughly to the center of the contact ellipse.

For the same conditions, Figure 10 shows the instantaneous resultant forces in planes perpendicular to the road surface and parallel to the direction of motion of the vehicle, that is, the resultant of the vertical and longitudinal components during the time of contact. It will be noticed that some of the series of forces parallel to the center line of the tire tread represent a longitudinal force-time curve having two peaks, some having three peaks. No reason can be given for the difference in the number of peaks; there was no obvious relationship between longitudinal peak number and stud height, deviation, speed, torque applied to the wheel, inflation pressure, tire size or wheel load. It is therefore reasonable to assume that the tread pattern is the cause; in other words, the number of peaks for the constant-speed condition depends on what

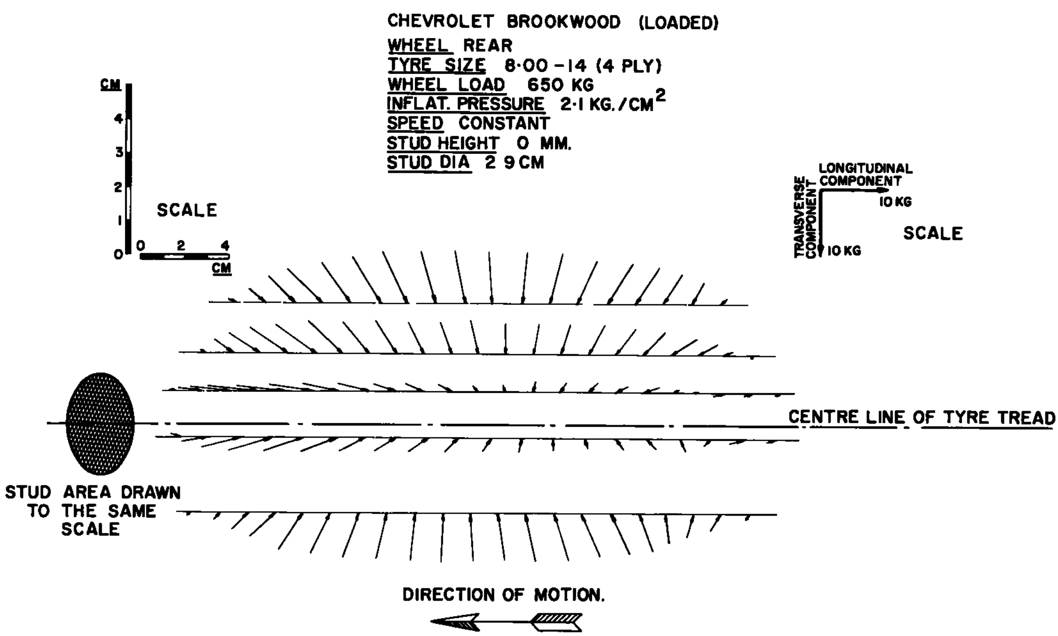


Figure 9. Vectorial diagram of resultant forces in the plane of the road over the contact area.

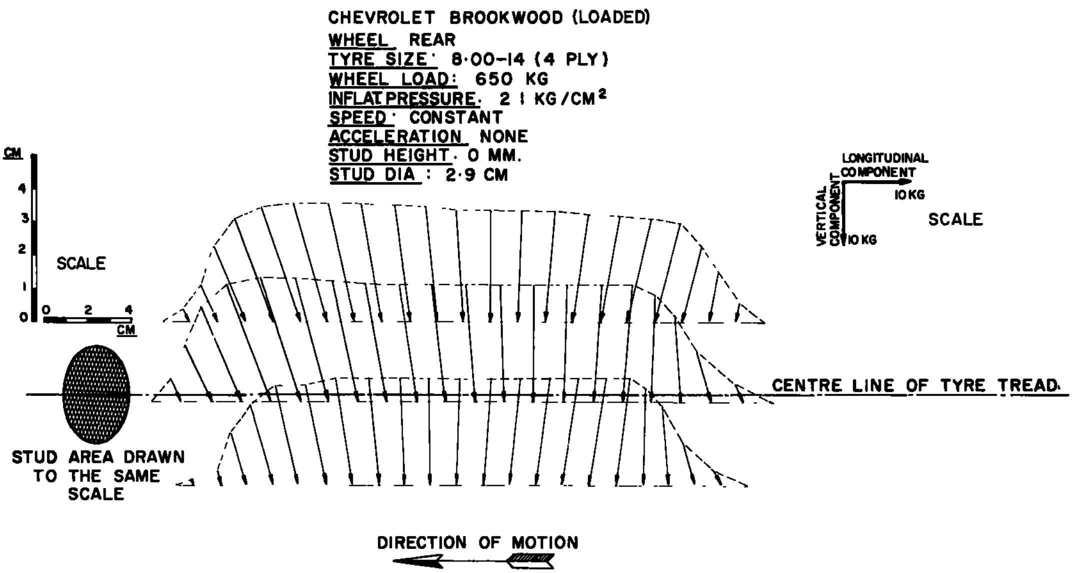


Figure 10. Vectorial diagram of resultant forces in three vertical longitudinal planes along the contact area.

part of the pattern comes into contact with the stud. In general about 75 percent of all tests carried out at constant speed gave three peaks for the rear wheel as well as for the front wheel.

Figure 11 gives again the instantaneous resultants of vertical and longitudinal components, plotted at short intervals of the contact time. As mentioned before, the peak force of the longitudinal component always occurs in the latter half of the contact time for acceleration as well as for deceleration. In the case of acceleration and deceleration, therefore, the greatest inclination of the vertical-longitudinal resultant is found just before the tire has rolled over the stud. This is independent of the stud height and of the tire and vehicle characteristics.

Peak Vertical Forces

The effect of the variables, listed at the beginning of this paper, on the measured force components will now be discussed. With so many variables it was not possible to vary each independently, but it is possible to draw some conclusions from the results and to indicate general trends. In most of the discussion on vertical forces which follows, the maximum force in a given trace is referred to; the shape of these traces has already been discussed.

Influence of the Deviation. It was found that the vertical peak force shows a characteristic distribution across the width of the tire, particularly pronounced for car tires and, in this case, clearly not very much influenced by the type of the tire pattern (Figs. 12, 13, 14 and 15). The vertical peak force increases with both positive and negative deviation and then decreases towards the edges of the tire as soon as only part of the stud area is covered by the tire tread. This particular distribution can be attributed to the influence of the side-walls of the tire which increase the stiffness along the edges of the contact area. This assumption is confirmed by an increase in difference between maximum peak force near the edges and the peak force at the tire center line with decrease in inflation pressure. It can also be seen that this difference increases with stud height but not as much as does the force at the tire center line.

The difference in peak force between the maximum and that at the tread center line is from 7 to 11 kg for the car tires and stud height zero, with the exception of the rear wheel of the Chevrolet sedan which showed a difference of about twice as much. At a stud height of 2.5 mm this difference increased to 13 to 24 kg for the car tires, and to 20 to 35 kg using a stud height of 5.5 mm.

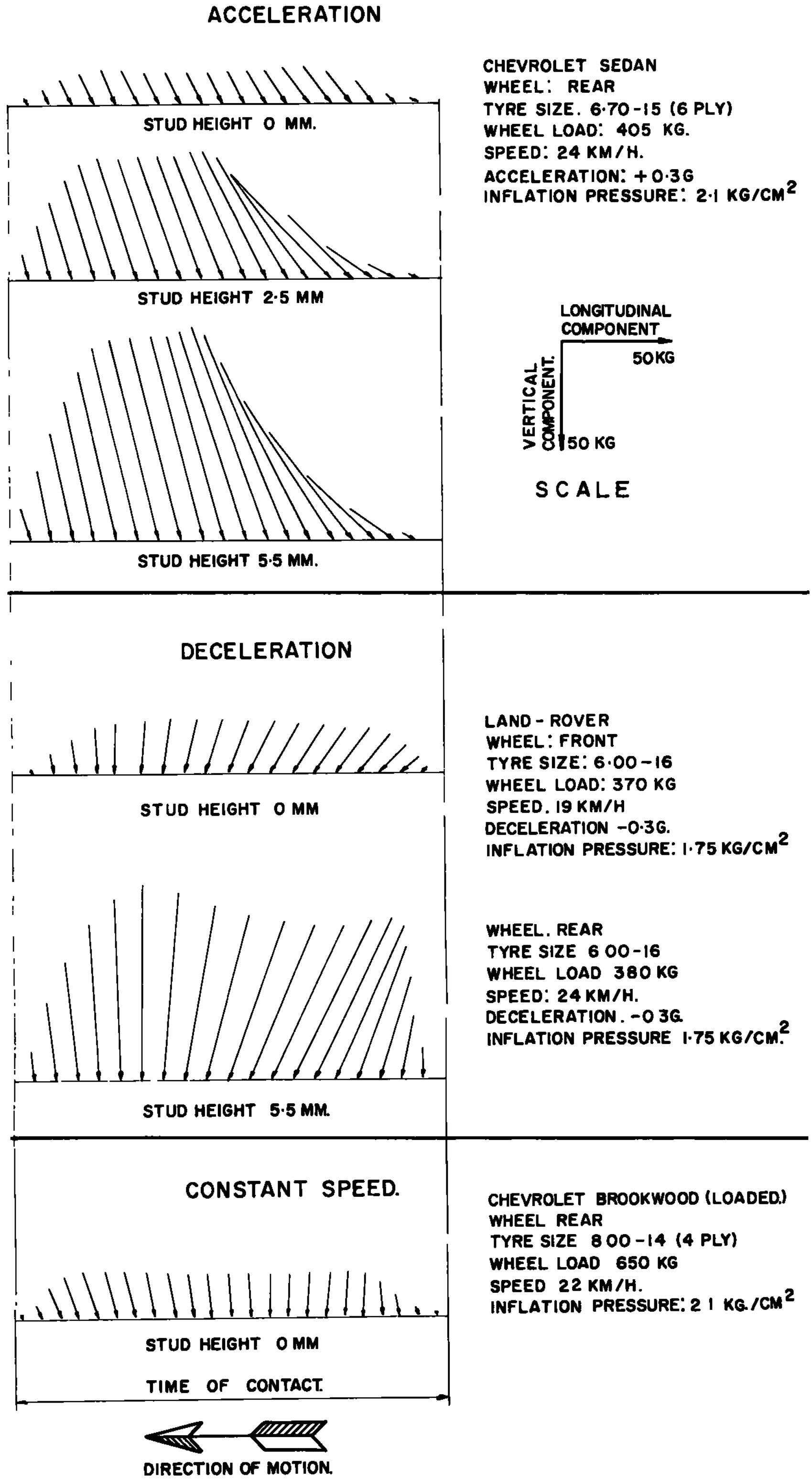


Figure 11. Effect of stud height and condition of motion of vehicle on the resultant forces in a vertical plane close to the major axis of the contact area.

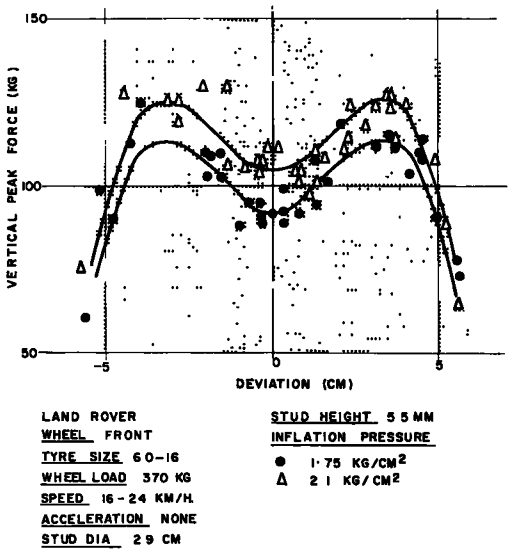


Figure 12. Influence of inflation pressure on the transverse distribution of vertical force at one stud height.

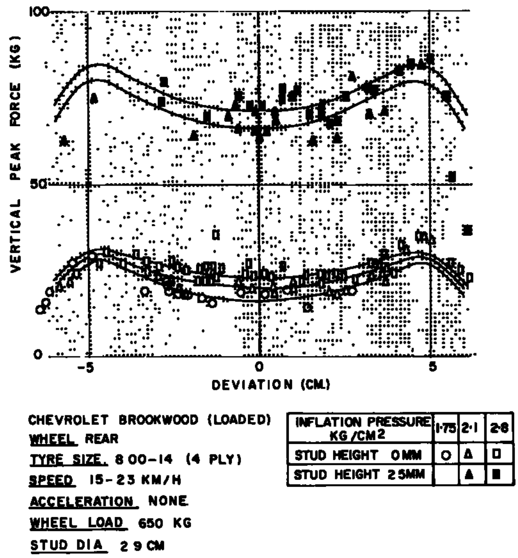


Figure 13. Influence of inflation pressure and stud height on the transverse distribution of vertical force.

The scatter of the test results obtained with the loaded trucks makes it difficult to give precise values, but Figures 16, 17 and 18 show at least the trend of increasing peak forces near the edges of the tire.

Influence of Inflation Pressure, Wheel Load and Tire Type. The influences of these three factors are interrelated. An increase in tire pressure decreases the contact area and, therefore, increases the mean vertical pressure within the contact area for a given wheel load. As shown in Figures 12, 13 and 16 the vertical peak forces,

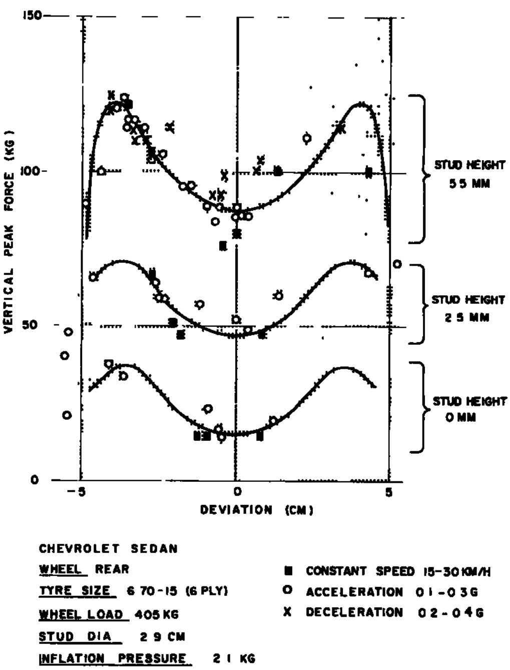


Figure 14. Influence of stud height and condition of motion on the transverse distribution of vertical force.

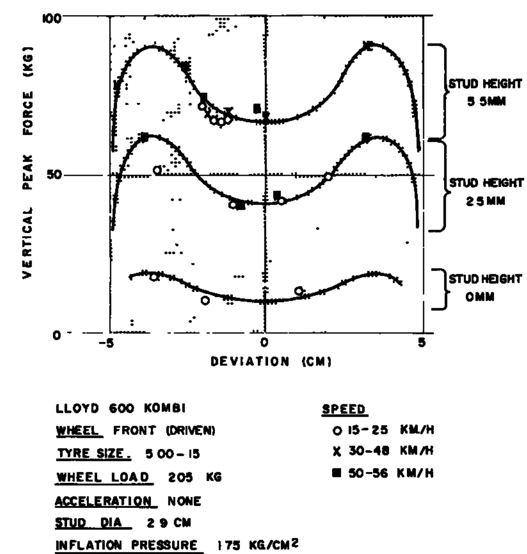


Figure 15. Influence of stud height on the transverse distribution of vertical force at different speeds.

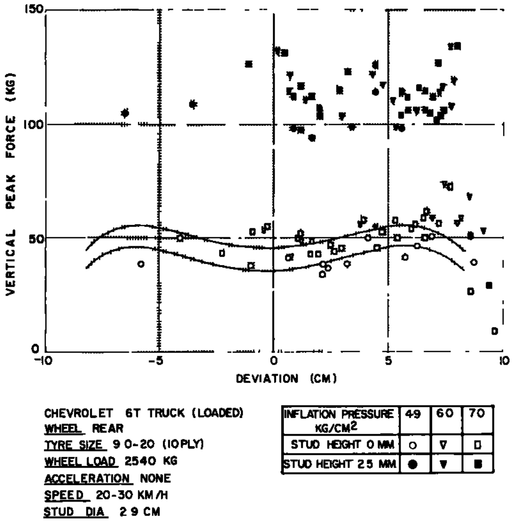


Figure 16. Influence of stud height and inflation pressure on the transverse distribution of vertical force for a heavy wheel load.

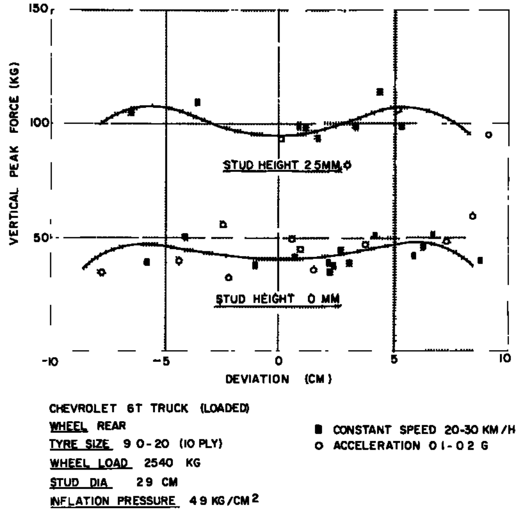


Figure 17. Influence of stud height on the transverse distribution of vertical force for a heavy wheel load at constant speed and accelerating.

however, also increase with inflation pressure. Although the vertical peak force at tread center line might not be expected to increase with a decrease in contact area, plotting vertical peak force at center line against inflation pressure (Fig. 19), in fact shows a definite relation. The points in Figure 19 are taken from tests using different

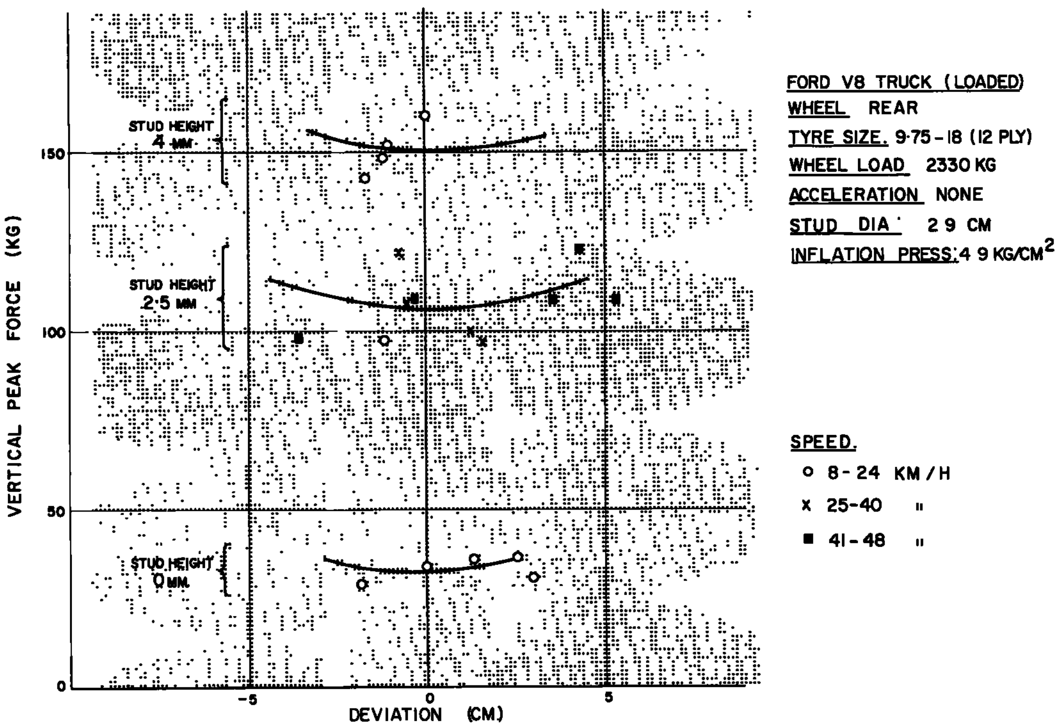
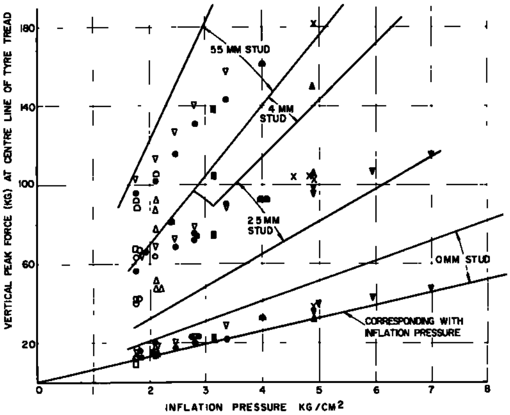


Figure 18. Influence of stud height on the transverse distribution of vertical force for a heavy wheel load at different speeds.



	WHEEL LOAD KG	TYRE SIZE	PLY
○	135	5 0-15	
□	205	5 0-15	
△	370-380	6 0-16	
Δ	405-420	6 70-15	6
▽	480	8 0-14	4

	WHEEL LOAD KG	TYRE SIZE	PLY
●	650	8 0-14	4
■	700	7 0-20	8
●	680	7 0-20	10
X	1780/2	7 50-20	10
▲	2330	9 75-18	12
▼	2540	9 0-20	10

Figure 19. Relation between vertical force on the tread center line and inflation pressure at various stud heights.

tires and vehicles, front and rear wheels, different wheel loads and traveling speeds. It can therefore be stated that the vertical peak forces at the tread center line depend primarily on the inflation pressure. Increasing the inflation pressure in the 8.00-14 tire, for example, with a wheel load of 480 kg gives an increase in the vertical peak force at tread center line but not in proportion to the pressure increase. Static tests have shown that the contact area does not decrease proportionally with an increase in inflation pressure, but to a smaller extent. A plot (not shown) of vertical peak force against an average pressure (calculated by dividing static wheel load by static contact area as taken from tire prints for different inflation pressures) gave a strictly proportional relationship independent of wheel load. It should be remarked that the 8.00-14 tires at wheel loads of 480 kg and 650 kg (Fig. 19) were not of the same make.

Influence of Speed. The test results have revealed no significant effect of vehicle speed on the magnitude of the recorded vertical peak forces, as shown in Figures 15, 18 and 20. In a recent paper Chiesa points out (10) that the increase in tire stiffness (in kg per sq cm) of a certain car tire at a wheel load of 350 kg and inflated to 2.0 kg per sq cm is only 10 percent if the speed is increased from 30 kph to 75 kph (19 mph to 47 mph).

Influence of Acceleration and Deceleration. Accelerating a vehicle increases the load on the rear wheels and decreases it on the front wheels by an amount de-

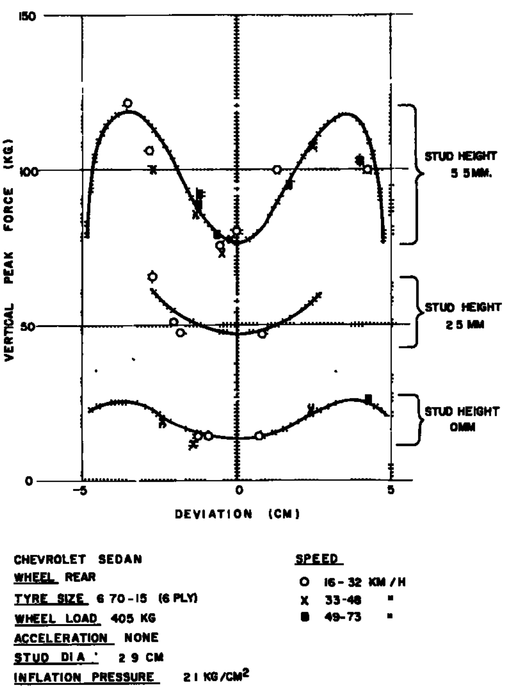


Figure 20. Influence of stud height on the transverse distribution of vertical force at different speeds.

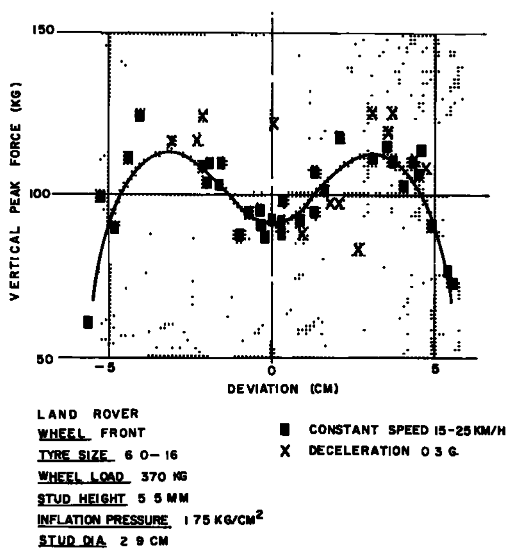
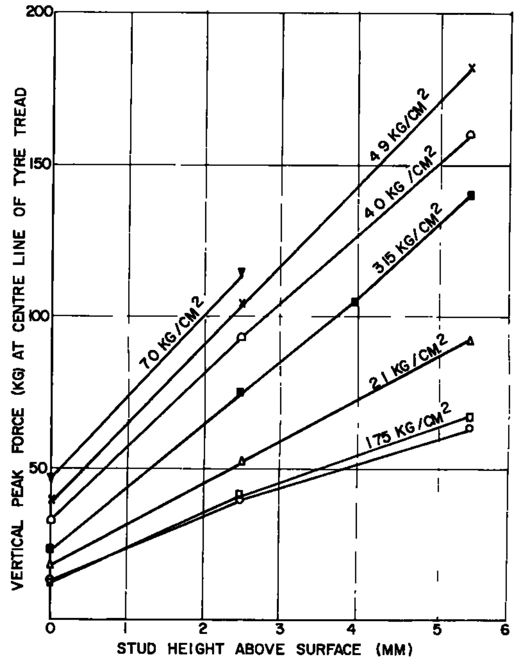


Figure 21. Influence of condition of motion on the transverse distribution of vertical force.

pending on the height of the center of gravity and the wheel base, etc. The results of some tests with various amounts of acceleration and deceleration are given in Figures 14, 17 and 21. Figure 14 shows that the recorded peak force (rear wheel) increases with deceleration despite the fact that the dynamic load on the wheel decreases with deceleration. This is explained by a change in shape of the force-time trace (Fig. 7f and g), arising from tire distortion under the high torque. In the case of the small acceleration of the Chevrolet 6-ton truck (Fig. 17) there is no significant difference in vertical peak forces at constant speed and in acceleration.

Influence of Stud Height Above Surface. Plotting the vertical peak force at the tread center line against stud height (Fig. 22) shows an almost linear relationship for the truck tires. In general, an increase in stud height from 0 to 2.5 mm results in an increase in vertical peak force at tread center line of 2.5 to 3 times in the case of the truck wheels. The relation varies for the Chevrolet Brookwood from 3 to 4.5 (Fig. 23). Increasing the stud height from 0 to 5.5 mm, the truck tires give a ratio of 4.5 to 6, and the car of 5 to 7.5.



	WHEEL LOAD KG	TYRE SIZE	PLY
O	135	5.0-15	
□	205	5.0-15	
Δ	420	6.70-15	6
■	700	7.0-20	8
◘	680	7.0-20	10
X	1780/2	7.50-20	10
▼	2540	9.0-20	10

Figure 22. Relation between vertical force on the tread center line and stud height at various inflation pressures and wheel loads.

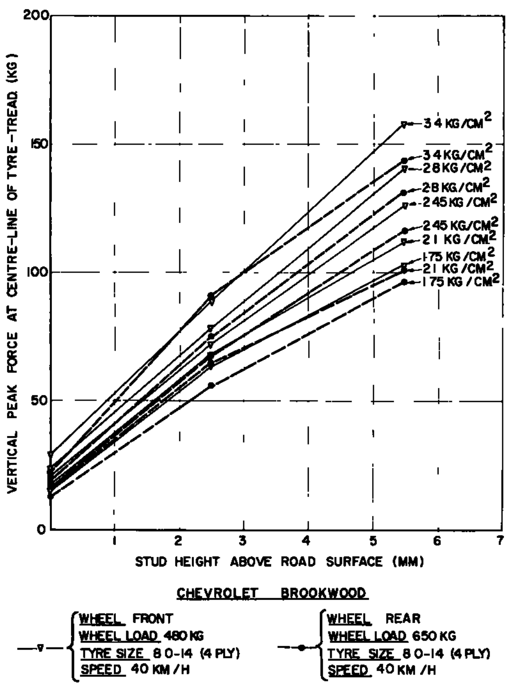


Figure 23. Relation between vertical force and stud height for various inflation pressures.

Longitudinal Horizontal Forces

Influence of Stud Height. At constant speed the magnitude of the longitudinal forces is so small in comparison to the vertical component that only a small increase in longitudinal peak forces with increasing stud height can be noted. The magnitude of the longitudinal peak forces applied by cars on the stud is of the order of up to 5 kg using zero stud height, up to 10 kg for stud height 2.5 mm and up to 15 kg for stud height 5.5 mm. The range of forces for trucks is up to 10 kg for zero stud height and up to 15 kg for 2.5 mm.

Influence of Acceleration and Deceleration. As can be expected, a variation in

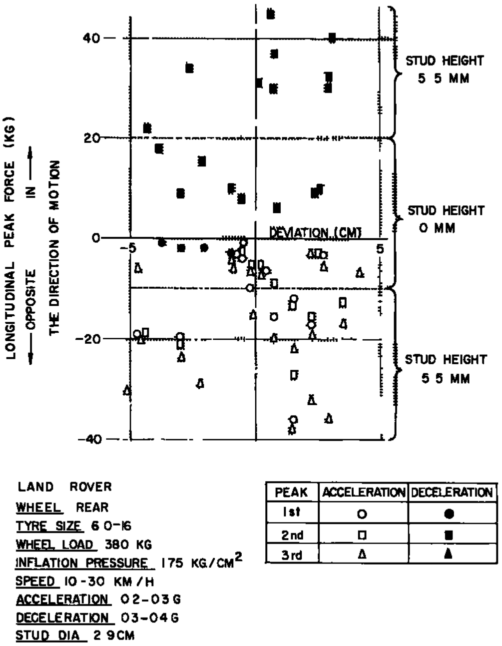


Figure 24. Influence of stud height and condition of motion on the longitudinal horizontal forces.

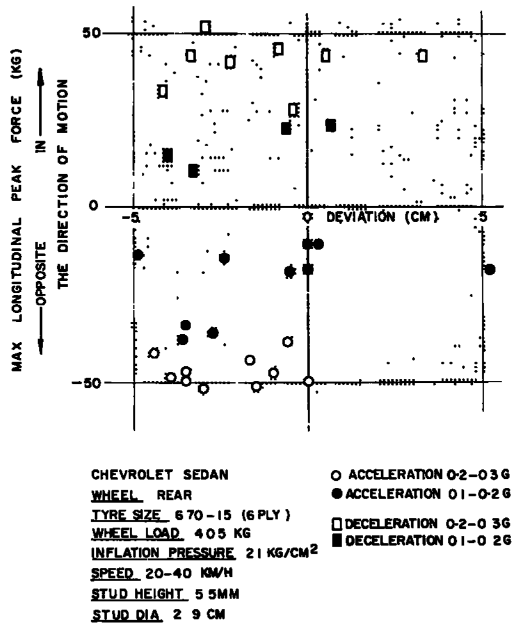


Figure 25. Influence of condition of motion on the longitudinal horizontal forces.

torque applied to a wheel has a big effect on the longitudinal force component. It has been already shown in Figure 7 that the shape of the longitudinal force-time trace varies considerably with the applied torque and also that the direction of the peak longitudinal force changes with a change in the direction of the applied torque.

Taking acceleration first, it can be seen in Figures 24 and 25 that the maximum peak forces (occurring in the latter half of the contact time) are of the order of up to 50 kg for the greatest stud height employed (5. 5 mm) using cars accelerated up to 0. 3 g.

In Figure 26 the maximum longitudinal peak forces are plotted against the degree of

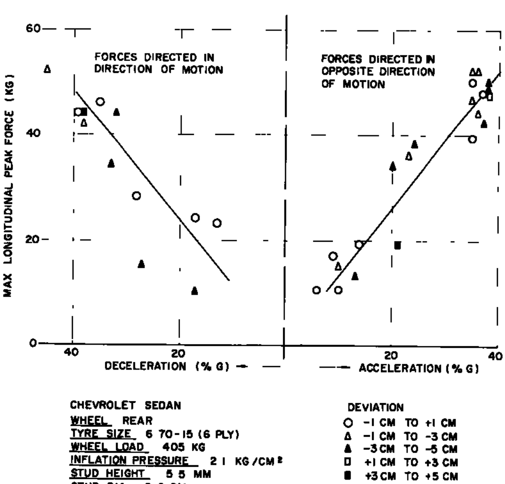


Figure 26. Relation between maximum horizontal longitudinal force and amount of acceleration.

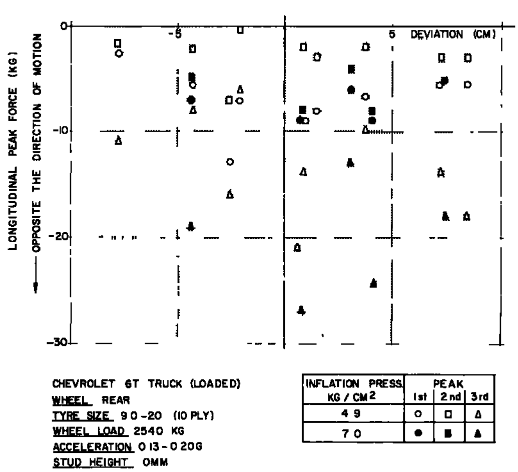


Figure 27. Influence of inflation pressure on the longitudinal horizontal forces for a heavy wheel load in acceleration at zero stud height.

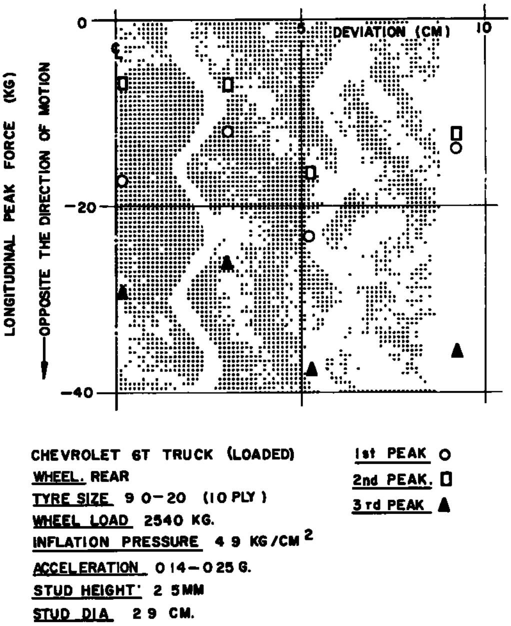


Figure 28. Longitudinal horizontal forces for a heavy wheel load in acceleration at 2.5 mm stud height.

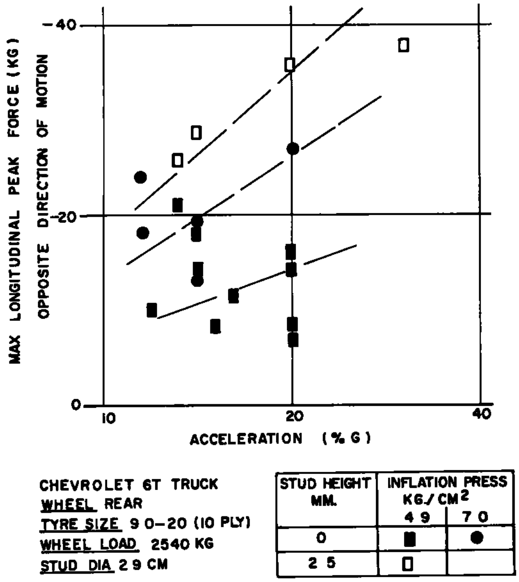


Figure 29. Relation between maximum longitudinal horizontal force and amount of acceleration for a heavy wheel load.

acceleration and deceleration for the rear wheel of a car, using a stud height of 5.5 mm. Figures 27 and 28 show the forces obtained by accelerating the Chevrolet 6-ton truck and the influence of the inflation pressure. Due to the greater driving force required for accelerating greater masses the longitudinal forces exerted by the truck are very much higher than those of the cars. Figure 29 shows the influence of degree of acceleration, with stud height and inflation pressure as variables, on the maximum longitudinal peak force exerted on the stud by a heavy truck tire.

Comparing the results obtained for deceleration and acceleration (Figs. 24 and

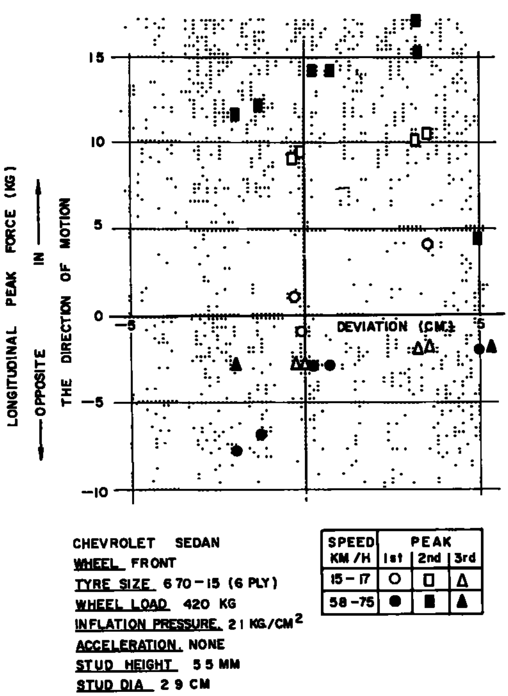


Figure 30. Influence of speed on the longitudinal horizontal forces.

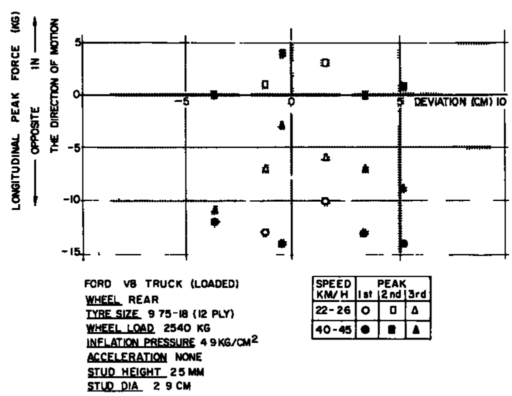


Figure 31. Longitudinal horizontal forces at two different speed ranges.

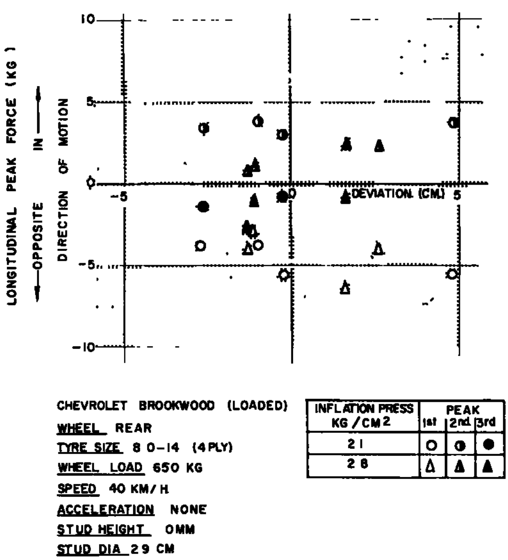


Figure 32. Longitudinal horizontal forces at zero stud height and two inflation pressures.

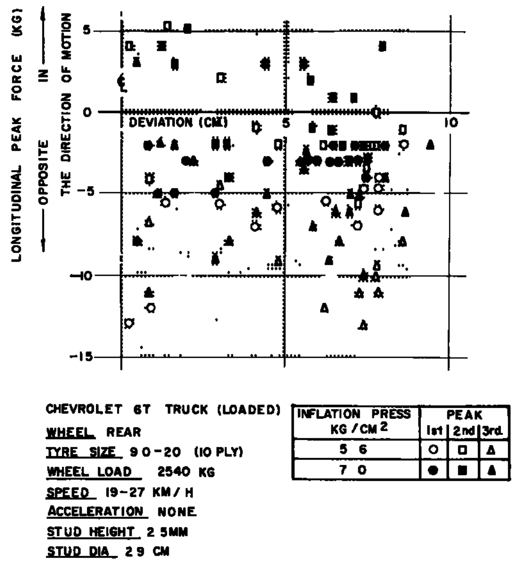


Figure 33. Longitudinal horizontal forces at two inflation pressures.

26), the same order of magnitude of peak forces is found in both cases if the stud height and inflation pressure are kept constant. The forces caused by deceleration, however, seem to be slightly smaller, which may be due to the effect of air resistance.

Influence of Speed. Some test results obtained at different speeds are given in Figures 30 and 31. If the stud is set at a height of 5.5 mm, increase in speed influences, particularly, the peak value in the direction of motion, that is, the second peak. This is illustrated in Figure 30 giving the results for a front wheel. This effect is also seen in Figure 31 giving results with a rear wheel.

Influence of the Deviation. The scatter in the longitudinal forces due to torque variations and tread pattern has not permitted any relationship with the deviation to be found, but it is probably safe to assume a fairly even behavior over most of the tire width with a decrease in longitudinal peak force near the edges of the track.

Influence of Inflation Pressure. The results obtained by using different inflation pressures under constant speed are given in Figures 32 and 33. For the stud flush with the road there is no obvious influence, and even at a greater stud height the effect of variations in torque seems to mask any possible effect of change in inflation pressure.

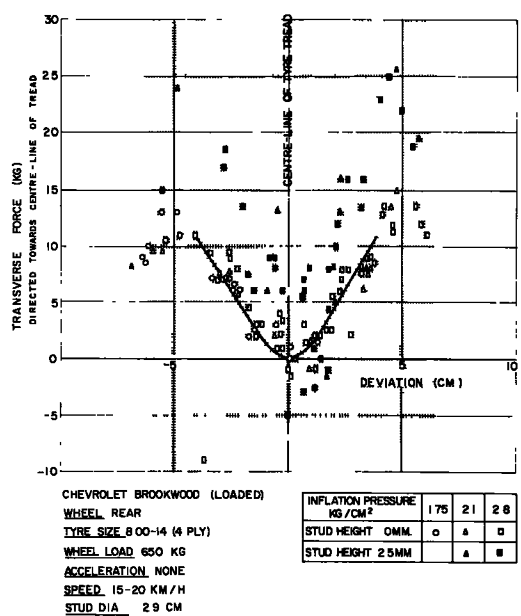


Figure 34. Influence of stud height on the distribution of transverse horizontal force at three inflation pressures.

Transverse Horizontal Forces

The magnitude of the transverse peak forces was also measured and typical results are shown in Figure 34 for the rear wheel of a loaded station wagon, with stud height and inflation pressure as variables.

As already mentioned, the direction of the transverse force is always towards the center line of the tire tread. However, very occasionally a small peak force of short duration in an outwards direction was recorded (the few negative points in Figure 34). This was attributed to irregularities in tread pattern or to small deviations from straight-line travel of the vehicle. It will be seen that the increase in transverse force with increasing deviation follows almost a parabolic curve outwards until only part of the stud surface is covered, when the force then decreases.

The influence of inflation pressure is again negligible on this horizontal component but the stud height has a marked effect, as shown in Figure 34. Some tests to measure this force component under a truck tire showed slightly greater forces than those under a car tire but, due to the greater width of the truck tire, the increase in force with deviation was not so steep. Variation in inflation pressure again produced no effect.

Force-Time Relations

From a study of the shapes of the force-time traces of the three components measured, the following observations have been made about forces generated under or very close to the tread center line.

1. The rise-time of the vertical force is 20 to 25 percent of the total time of contact at zero stud height, 28 to 32 percent at 2.5 mm and 32 to 36 percent at 5.5 mm. The time during which the vertical force decreases almost linearly is of a similar order, thus leaving for the horizontal part of the vertical force-time curve about 50 percent of the contact time at zero stud height, about 35 percent at 2.5 mm and 30 percent at 5.5 mm.

2. The rise-time of the longitudinal horizontal force under constant speed conditions to reach the first peak is slightly shorter than that of the vertical force—about 18 percent at zero stud height and about 28 percent at 2.5 mm and 5.5 mm. The time between the first and second peaks varies between 30 and 60 percent of the contact time, depending on stud height and on whether there are two or three peaks; the curve, however, at zero stud height shows the longest time between the first and second peaks.

The time between the second and third peaks is up to 5 percent less than the rise time to reach the first peak, and the time from the third peak to the end of contact is between 9 and 15 percent of the total time of contact, the higher values occuring at greater stud heights.

3. The transverse force-time curves are shaped like half a sine-wave.

4. In general, in order to express the total resultant force at a point on the road surface to a first approximation in terms of an equivalent frequency of sinusoidal loading, the effective contact length can be taken as a half wave-length. From measurements of the force-time traces for cars the average contact length is about 23 cm at zero stud height. As this figure includes the finite size of the recording stud at both ends of the contact area, 5 cm (say) should be subtracted from this figure, giving a typical effective (point) contact length of 18 cm. At a speed of 10 kph (6.2 mph) this gives an equivalent frequency of about 7.7 cps, or at 80 kph (50 mph) a frequency of 62 cps.

For the trucks used in this work the mean contact length (expressed at a point) was 27 cm which gives an equivalent frequency of 5.1 cps at 10 kph, or 41 cps at 80 kph.

CONCLUSIONS

The discussion given above has dealt with many of the detailed points that have emerged from this work. Many of these points need not be referred to again here. However, it may be useful to summarize a few of the general findings in this investigation. It should be pointed out that the results obtained in this work are based on the recording of forces exerted on an area of 1 sq in. (6.5 sq cm) of a road surface. Somewhat different results might be expected if the stud area were significantly greater or smaller than that used.

The Influence of Various Factors

1. The vertical force component is influenced mainly by the inflation pressure, the deviation, and the stud height.
2. The longitudinal force component is influenced mainly by the torque applied to the wheel and the stud height.
3. The transverse force component is influenced mainly by the stud height and the deviation.
4. Under normal, smooth-running conditions speed, as such, has no significant influence on the forces recorded.

Maximum Vertical Forces

1. For an inflation pressure of 28 psi (2 kg per sq cm) the vertical peak force during the time of contact at tire center line is in the range from 30 to 44 lb on 1 sq in. (2.1 to 3.1 kg per sq cm) at zero stud height, 100 to 155 psi (7 to 11 kg per sq cm) at 2.5 mm stud height, 155 to 240 psi (11 to 17 kg per sq cm) at 5.5 mm stud height. The ranges for an inflation pressure of 70 psi (5 kg per sq cm) are respectively 70 to 88 psi (5 to 6.2 kg per sq cm), 210 to 240 psi (15 to 17 kg per sq cm) and about 400 psi (28 kg per sq cm).
2. The maximum vertical peak forces are exerted near the edges of the track and they are 15 to 24 psi (1 to 1.7 kg per sq cm) greater than those measured at the tread center line at zero stud height.

Maximum Horizontal Forces

1. The longitudinal horizontal force component develops usually three peaks during the time of contact at constant speed. If a greater torque is applied to the wheel, as in accelerating or decelerating, the force-time curve deteriorates to a single-peaked curve. The magnitude of the longitudinal peak forces at constant speed is less than 11 psi (0.8 kg per sq cm) for car tires at zero stud height, up to 22 psi (1.5 kg per sq cm) at 2.5 mm stud height, and up to 33 psi (2.3 kg per sq cm) at 5.5 mm. For trucks these values are up to 22 psi (1.5 kg per sq cm) at zero stud height, and up to 33 psi (2.3 kg per sq cm) at 2.5 mm.
2. Under acceleration or deceleration (up to 0.4 g) longitudinal peak forces of up to 40 psi (2.8 kg per sq cm) at zero stud height were recorded and up to 110 psi (7.7 kg per sq cm) at 5.5 mm stud height.
3. The transverse horizontal component is zero at the center line of the tread and increases up to 33 psi (2.3 kg per sq cm) near the edges of the track at zero stud height, and up to 55 psi (3.9 kg per sq cm) at 2.5 mm. The direction of the transverse component is always towards the center line of the tire tread.

ACKNOWLEDGMENTS

The investigation described in the paper was carried out as part of the program of research of the National Institute for Road Research in Pretoria. The National Physical Research Laboratory in Pretoria designed the stress recorder which was built in the C.S.I.R. Central Workshop. J.B. Basson, T.B. Partridge and A.F. Reyneke assisted with the experimental work. The authors wish to thank P.J. Rigden for his advice and interest and for help in the preparation of the manuscript. The paper is published by permission of the South African Council for Scientific and Industrial Research.

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Appendix

The translation of mechanical deflections into electrical signals is achieved by means of two Blumlein capacity bridges which are particularly sensitive to capacity changes. The capacity changes are effected by means of a set of three condenser plates for each of the spring systems as shown in Figure 35. Since the electronic circuits for the horizontal and vertical force measurements are identical, only the one branch (say for vertical forces) need be described.

The outer plates of the two condensers, C_1 and C_2, which make up the two arms of the bridge, are fixed, while the common inner plate can move proportionally to the vertical force and is electrically earthed. Any movement of the center plate which increases C_1 will correspondingly decrease C_2 and vice versa.

The ratio arms of the bridge consist of two inductances, L_1 and L_2, wound on the same ferrite core in such a way that the mutual inductance between the windings is the same as the self-inductance of each. The inductances are further arranged in the bridge so that the effect of the mutual inductance with reference to one is such that it opposes the self-inductance of the other. The bridge is fed with a carrier frequency of 150 kilocycles per sec.

The bridge is initially balanced for the central condenser plate in the undeflected position. A movement of this plate results in a bridge output voltage proportional to the deflection. The force-deflection relationship is actually slightly curved (see Fig. 6) and the magnitude of the output voltage V_0 depends on the input voltage V_i as well as on the carrier frequency. In practice, V_i is kept constant and the carrier frequency kept at a value where the change in the response of the bridge is negligible for a small change in frequency.

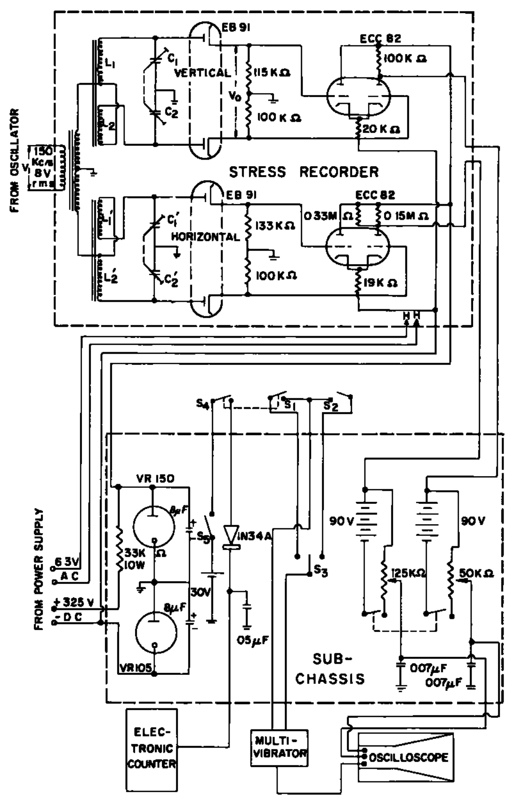

Figure 35. Electrical diagram.

The output voltage V_0 is rectified in a discriminator-type detector and amplified in a direct-coupled amplifier from which it emerges with a superimposed DC voltage. This DC voltage is cancelled by means of a dry battery and potentiometer before the signal is fed to the Y_1 plate of a double beam oscilloscope. A similar signal proportional to the horizontal force is fed to the Y_2 plate.

In order to photograph the traces when the wheel passes over the measuring stud the oscilloscope beam-sweeps are triggered by means of specially modified car dip switches which are actuated by the tire immediately before it reaches the force measuring stud.

The switching system is as follows: S_1 and S_2 are two micro-switches installed on either side of the force-measuring stud to facilitate triggering in either direction. S_3 is a switch fitted on the sub-chassis which can put either the signal from S_1 or from S_2 into circuit, depending on the direction from which measurement is to be made. The triggering pulse is then fed to the multi-vibrator unit where every second pulse is selected to trigger the oscilloscope. This enables either the front or back wheel of the car to be recorded. The selective triggering is achieved by means of neon indicators fitted in the anodes of the flip-flop stages of the multi-vibrator unit. Depending on the setting of the trigger level of the oscilloscope, neon indicator No. 1 will show that the just-triggered tube will be seen on the oscilloscope, that is, the front wheel. Neon indicator No. 2 in turn will indicate that the second pulse will trigger the oscilloscope, that is, the pulse given by the back wheel of the vehicle.

An additional switch, S_4, actuated simultaneously with S_1, is used to provide pulses from both the front and the back wheel. These pulses start and stop a micro-second electronic timer to provide a means of measuring the vehicle speed, using the known distance between the front and rear wheels.

Discussion

H. J. H. STARKS and A. C. WHIFFIN, Road Research Laboratory, Harmondsworth, Middlesex, England—The paper is interesting and provides useful data in a field where little information is available. For this reason, it is regretted that the authors have not given detailed information concerning the properties of the tires which they used and compared their results with those reported by earlier workers.

In Figures 12 to 21 of Bonse and Kühn's paper, the distribution of pressure across the width of the tire contact area is shown usually as a double-humped curve, giving higher pressures near the tire wall than in the center of the contact area. In Figure 1 of Markwick and Starks' paper, to which the authors refer in their introduction, double-humped curves were shown only for tires which were overloaded while curves having a central peak pressure were obtained with normally loaded tires. More recent work at the Road Research Laboratory, in which the vertical compressive stresses are measured within the road surfacing, have confirmed the curves reported by Markwick and Starks. The tire wall might be expected to have an effect with a normally loaded tire in cases where the pressures are recorded by studs which protrude above the road surface, but some of the diagrams shown by Bonse and Kühn refer to studs flush with the road surface. Was there anything special about the tires or treads used by the authors, and were some of them made of synthetic rubber?

Markwick and Starks showed that the mean pressure "p" on a cylindrical plunger of radius "a" projecting by an amount "z" into a semi-infinite elastic solid of elastic modulus "E" and Poisson's ratio "m" was given by the formula:

$$p = \frac{2E}{\pi(1 - m^2)} \quad \frac{z}{a}$$

Although Bonse and Kühn do not refer to this earlier theoretical and experimental work in detail, Figures 12 and 13 of their paper confirm that a linear relation exists between p and z/a. They, however, do not give figures for the hardness of the rubber used in their tires, from which the elasticity might have been inferred, so it is not possible to use their data to investigate the relation between normal pressure and hardness of the tread rubber.

Road engineers are as greatly interested in the forces between tires and fine-textured road surfaces as in those resulting from protruberances of the type represented by the stud heights of 2.5 and 5.5 mm employed by the authors. It is a pity, therefore, that the oscillograms given in Figure 7, showing the vertical and longitudinal forces for several degrees of acceleration and deceleration, refer only to a stud height of 5.5 mm. Admittedly, Figure 8 gives two oscillograms of the vertical and transverse forces for a stud set flush with the road surface, but it deals only with the steady velocity conditions. The oscillograms in Figure 8 are smoother than those in Figure 7 and there is no doubt that some of the irregularities shown in Figure 7 arise from the protruding stud. When Markwick and Starks used a stud set flush with the surface of the road and a tire running freely without change of velocity, they obtained a record of longitudinal pressure of the form shown by the upper trace of Figure 7e. The two areas between these lines and the axis represent the forces working in the forward and backward direction, so that their net difference represents the tractive force. The authors have made no attempt to deduce tractive forces from their measurements, but it would be of considerable interest if they would look into this for it gives much information as to the reliability of the data.

It is very difficult to see precisely what is being measured by a stud 2.9 cm in diameter protruding 5.5 mm above the road surface. It must deflect as a cantilever under the applied force and this will relieve some of the pressure and introduce errors of measurement. Have the authors looked into this? Also, what interpretation do they place on the data obtained with the protruding studs, and how do they propose to apply this information to normal road surfacing problems? In this connection, the information given in Figures 24 to 28 is particularly difficult to understand. Figure 26 shows that the maximum longitudinal force varies markedly with the deceleration or acceleration of the tire, the slopes of the lines being 1.2 kg for a change of deceleration of 1 percent g. Figure 27, however, shows a plot of horizontal forces covering the range 13 to 20 percent g which would alter a force of 10 kg by as much as 8.4 kg.

It is difficult to obtain data from this report concerning the important relation between vertical pressure, inflation pressure and wheel load. In the discussers' experiments, when the wheel load is not sufficiently great to overload the tire, it was found that increase of wheel load merely causes an increase in the tire contact area and little change in the vertical pressure. At constant wheel load, increase of inflation pressure reduces the ratio of peak vertical pressure to inflation pressure from nearly 3 at very low tire pressures to 1.5 at very high pressures, the ratio for the normal working pressure of the tire being about 2.0. This recent work at the Laboratory confirms that done before the war by Markwick and Starks.

Markwick and Starks used a plunger ⅛ in. in diameter with its end normally set flush with the road surface. When their results were assembled together to derive the longitudinal and transverse distributions of pressure, it was found that the pressure fell to zero in those portions of the tire tread where no rubber came into contact with the road surface. Bonse and Kühn use a stud which is 1.14 in. in diameter and, therefore, incapable of showing these effects of the tire tread. The tires they used, however, had large tread patterns and these may have caused some scatter of their results. Have the authors considered this and can they suggest how their results would be affected by the use of plungers of other dimensions and shapes?

R. P. H. BONSE and S. H. KÜHN, Closure—The authors wish to thank Dr. Starks and Dr. Whiffen for their comments on the paper. The reference to Figures 12 to 21 and the relation of these results to those published by Markwick and Starks calls for some clarigication. Results presented in Figures 13, 16, 17 and 18 actually refer to overloaded tires. Figures 12 and 21 concern tests where a stud height of 5.5 mm was used and where double-humped curves could be expected in any case except perhaps for grossly underloaded conditions. Apart from Figure 19, which does not refer to pressure distributions at all, Figures 14, 15 and 20 remain to be considered. It should be pointed out that the results presented in Figure 1 of the paper by Markwick and Starks referred to a 3.00 x 20 motorcycle tire with an inflation pressure of 50 psi (3.5 kg per sq cm), which was considered to be overloaded at 336 lb. Comparing this with a modern motorcycle tire of 3.00 x 19, it is found that this can carry a normal load of 400 lb at an inflation pressure of only 27 psi (1.9 kg per sq cm) (1). The authors doubt whether the results obtained on a pre-war motorcycle tire can be compared with those obtained with modern low-pressure car tires as referred to in Figures 14, 15 and 20. Modern tires are specifically designed to give higher flexibility and it can be assumed that, even under loads of 60 percent (Fig. 15) and 85 percent (Figs. 14 and 20) of the recommended maxima, "overload" conditions will be found comparable with tire behavior described by Markwick and Starks.

Regarding the question of the relationship between the formula derived by Markwick and Starks and the authors' results shown in Figures 12 and 13, the authors are unable to see any obvious correlation, but assuming that Dr. Whiffen and Dr. Starks meant to refer to Figures 22 and 23, it is agreed that there is a linear relationship between vertical peak force on the stud at the center line of the tires and the stud height, provided that the inflation pressure is kept constant. The authors consider that the vertical force exerted on a projection (or on a smooth surface) at a specific point across the tire width is a function of the height (and probably also of the diameter) of the projection, the stiffness of the tire carcass, the inflation pressure and the wheel load. The magnitude of the vertical force on the stud will furthermore depend on the position across the tire width at which it is measured. For projections of small diameters the tread rubber stiffness may become a major contributing factor, but this aspect was not investigated.

The oscillograms shown in Figures 7 and 8 were included as typical illustrations of the records obtained. The results extracted from a large number of oscillograms taken during the tests were given in the rest of the figures. The authors cannot see that calculation of tractive forces could have verified the feasibility of the data.

The authors decided on a circular stud of 1 sq in. in area with height adjustment instead of the very small stud (projecting 0.01 in.) used by Markwick and Starks because the 2.9-cm diameter stud was robust, would not lodge in the grooves of the tire and so result in a larger scatter of the results, and was only slightly larger in area than typical large stones used in some surface dressing work in South Africa. The beams supporting the stud were designed to deflect only slightly under load, the horizontal deflection being 0.002 in. for a maximum horizontal force of 60 kg and the vertical deflection being 0.002 in. for a maximum vertical force of 200 kg. It is considered that these deflections would not significantly affect the forces measured. Measurements on a projecting stud were included since it is believed that failure of a surface dressing often occurs through the dislodging by traffic of stones that project from the general level of the surface. The results presented in Figures 24 to 28 were included with the object of giving engineers some idea of the order of magnitude of the more severe forces likely to be exerted on projecting stones.

Dr. Whiffen and Dr. Starks should refer to Figure 19 in connection with the difficulty they mention in obtaining information concerning the relation between vertical pressure, inflation pressure and wheel load in the paper. It will be noticed from this figure that the vertical peak force on the stud varies significantly at constant wheel load with the inflation pressure. It is quite possible that the total vertical force over the contact area of the tire may remain substantially constant, but all the results referred to in this paper deal only with forces acting on the stud, and this must be borne in mind in reading the paper. It is also found from Figure 19 that the ratio of vertical peak force on the stud to the inflation pressure is not changed (within the experimental scatter) by an increase in the inflation pressure, regardless of the wheel loads involved, provided the stud is level with the road surface. For conditions where the stud height is increased above the surface this ratio does change with an increase in inflation pressure.

The tire tread pattern definitely resulted in a scatter of the results, as was found from tire prints taken at each determination on the road during the tests. On the question of the effects of different shapes and dimensions of studs, in conjunction with the tread pattern, on the results obtained, the following comments are put forward.

As the cross-section of the plunger is decreased one may expect the stiffness of the tire tread to become more important in determining the unit vertical pressure on it, in other words the effects of inflation pressure and tire carcass stiffness will become less important. This, in turn, may affect the shape of the double-humped curves found in the transverse distribution of vertical forces. Provided there is no slip between tire and road surface the unit horizontal and transverse forces may be expected to be virtually unaffected. When the stud is of small diameter it may fall wholly or partially in the grooves of the tire tread, resulting in a considerable increase in the experimental scatter.

The influence of the stud shape is more difficult to assess but one may again expect that the rubber stiffness will have a more pronounced effect when the shape of the stud tends to a sharp point with a probable increase in the unit pressures at the sharp points, as was found by Markwick and Starks. The observations in regard to flat studs will probably apply to the average unit vertical pressures on shaped studs of equivalent effective diameter. The unit horizontal and transverse forces may again be considered to be unaffected in the absence of slip.

REFERENCE

1. Bosch, K.F.Z., "Technisches Taschenbuch." 11 Auflage, Deutscher Ingenieur Verlag, Düsseldorf (1952).